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Does Soil Surface Roughness Increase or Decrease Water and Particle Transfers?

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ABSTRACT

Most of prior research showed increasing soil roughness delayed runoff and reduced total runoff and sediment yields but failed to differentiate roughness effects on water runoff and on sediment production. This study was conducted to assess separately the effects of soil surface depressions on runoff initiation and water and particle fluxes. A 5-m long soil box, filled with a silt loam, was split into 0.6-m wide paired smooth vs. rough plots with manually formed depressions, and subjected to a sequence of 24 mm h^{-1} simulated rainstorms at 5% slope. Eight experiments were conducted under different upstream inflows and subsurface regimes (drainage or seepage). Collected data include time to runoff initiation and fluxes of water and particles after an apparent steady state was reached. Depressions delayed the runoff initiation by storing water into puddles and enhancing infiltration. Once runoff reached an apparent steady state, surfaces with initial depressions produced 10% greater water flux than the initially smooth surfaces, regardless, the subsurface moisture regime. Roughness had no significant effect on steady-state particle flux and concentration. Our results indicate that the only assured soil and water conservation benefit from surface depressions is due to the delay in runoff initiation at the beginning of the rain event before the entire surface is contributing to runoff.

Most of the literature on soil surface roughness is focusing on its mathematical description and on how it evolves under rainfall (Linden and van Doren, 1986; Römkens and Wang, 1987; Lehrsch et al., 1988; Bertuzzi et al., 1990; Borselli, 1999; Dong et al., 1999; Hansen et al., 1999; Kamphorst et al., 2000). The rare studies trying to quantify the roughness effect on water runoff and soil loss usually show a decreased runoff and sediment production with an increased roughness (Johnson et al., 1979; Steichen, 1984; Cogo et al., 1984). A typical rationale for the roughness effect is from water and sediment trapping because rough surfaces contain many depressions and barriers that can decrease flow velocity, and hence the detachment power and transport capacity of the flow. Furthermore, since surfaces with higher roughness seal less rapidly, they tend to have a larger infiltration rate than those with lower roughness (Cogo et al., 1984).

This kind of roughness effect has been incorporated into erosion assessment tools such as Universal Soil Loss Equation (USLE) and its revised version (Revised USLE or RUSLE) (Renard et al., 1997). This commonly accepted roughness scenario compounds the runoff production into sediment production, that is, the reduced erosion is caused by a reduced water runoff. Hence it does not differentiate between the roughness effect on water runoff and the roughness effect on sediment production.

Even in a process-based model, such as the Water Erosion Prediction Project (WEPP), where the process of runoff production supposedly has been isolated from the sediment production, an increased surface roughness also results in an overall reduction in sediment delivery. In WEPP, an increased surface roughness causes a decrease in interrill sediment delivery and an increase in critical shear resistance in the rills (Flanagan and Nearing, 1995).

Despite the dominance of research results and predictive models showing that an increased roughness decreases erosion, there is evidence pointing the other direction. Burwell et al. (1968) and Burwell and Larson (1969) showed that after runoff had initiated, a rougher surface might not have the distinctly higher infiltration as a smooth surface as shown before runoff. The laboratory study of Helming et al. (1998) showed that while runoff was marginally affected, rough surfaces did show a greater soil loss than smooth surfaces because flow concentration may cause a localized increase in erosion. On the other hand, surface depressions that trap sediment and surface mounds that increase flow meandering (or resistance) may lead to a reduced sediment delivery. Therefore, the net roughness effect on sediment delivery depends on the balance between these opposing processes, and erosion can either increase of decrease as soil roughness is increased.

The effect of surface roughness on runoff was often associated with surface storage capacity, that is, volume of water puddles (Mitchell and Jones, 1976; Moore and Larson, 1979; Onstad et al., 1984; Moran and Vézina, 1993; Hansen et al., 1999; Kamphorst et al., 2000). Conceptually, the rainfall-runoff process can be divided into three stages and surface roughness may affect each of them. Stage 1 is mainly for surface wetting and depression filling and ends when runoff starts at the point of observation. Time to runoff is usually used to characterize this stage. Stage 2 is mainly associated with the rising portion of the hydrograph as the runoff contributing area expands. At Stage 3, runoff reaches a plateau or an apparent steady state when the entire surface is contributing runoff. Prior research indicates the importance of quantifying soil erosion at apparent steady-state runoff when the full detachment and transport potentials have been reached (Huang, 1998; Huang et al., 1999; Zheng et al., 2000). However, most prior roughness studies considered a fixed amount of rain and compared the runoff and sediment productions from rough vs.

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Abbreviations: WEPP, Water Erosion Prediction Project.

smooth surfaces. Such an approach lumps the effects of at least the first two runoff stages and does not allow a comparison of the true roughness effect under full runoff, or Stage 3. Since sediment production is closely linked to runoff production, factors affecting runoff generation during a rainfall event, such as initial wetting, depressional storage filling and infiltration, need to be isolated first before a meaningful comparison in sediment production can be made.

The roughness effect on erosion can be further compounded by surface and subsurface factors affecting soil erosion, because erosion process itself also causes a change in surface morphology or microtopography. Recently, the near-surface hydraulic gradient, that is, drainage and seepage, has been shown to significantly affect erosion (Bryan and Rockwell, 1998; Huang and Laflen, 1996; Huang, 1998; Owoputi and Stolte; 2001). How the roughness effect interacts with the hydrologic condition in runoff and sediment production has not yet been quantified.

Soil surface roughness is usually partitioned into oriented roughness and random roughness (Römkens and Wang, 1986). In previous studies, changes in random roughness were mainly from changes in aggregate-size distribution. The objective of this study was to compare runoff and sediment productions from two types of roughness, that is, a smooth surface and a surface with mound-and-depression pattern, under different near-surface hydraulic gradient and surface flow conditions. Runoff samples were collected and analyzed from side-by-side, smooth vs. rough plots under simulated rainfall with and without run-on. Runs made with rain only simulate the conditions prevailing at the upper boundary of a hillslope where there is no upstream contributing area. By adding run-on, we aim to reproduce the flow conditions encountered along a hillslope. The present approach studies separately the effect of roughness on the duration of the first stage (or time to runoff initiation or runoff delay) and on the water and particle fluxes at apparent steady state, that is, during Stage 3. An analysis of the roughness effect under a range of surface and hydrologic conditions provides a better understanding on how soil roughness actually affects the runoff and particle production.

MATERIALS AND METHODS

Experimental Setup

The experiment was conducted in the laboratory under simulated rainfall. The soil was collected from the surface horizon of an Ava silt loam (fine-silty, mixed, active, mesic Oxyaquic Fragiudalf with 15% sand, 70% silt, and 15% clay) at Sullivan County, IN (USA).

The experimental setup consisted of two soil boxes up and down slope to each other that could be either run independently or connected together. The upslope feeder box was used to vary the inflow to the downslope study box (Fig. 1). Each box had separate rainfall simulators mounted above, thus, enabling us to rain simultaneously on both boxes with different rainfall intensities.

The feeder box was 1.8 m long and 1.2 m wide. The study box was 5 m long and 1.2 m wide. Both boxes were 25 cm

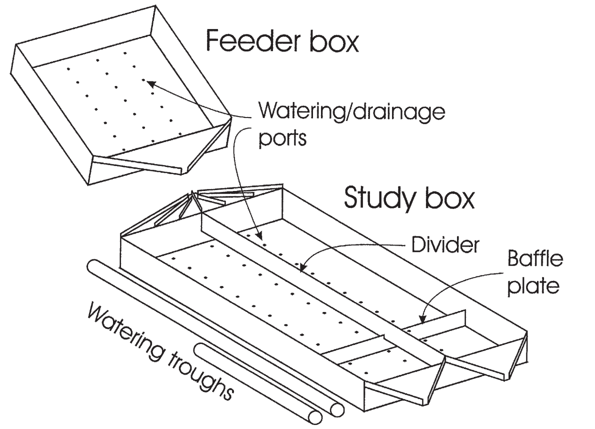

Fig. 1. Experimental setup showing the soil boxes and the watering troughs used to implement the seepage condition. Pipes connecting the troughs to the base of the box are not shown.

deep and filled with 5 cm of sand at the bottom and with 20 cm of soil on top of the sand layer. The two layers were separated from each other by a landscape fabric. Both soil boxes could be adjusted in slope and a system of watering troughs controlled the hydrostatic pressure at the bottom of each box independently by adjusting the height of the water level in the troughs. The feeder and study boxes could be run separately or connected together.

A baffle plate was set up 1 m from the outlet of the study box to reduce the edge effects due to excessive seepage at the lower part of the box. Metal plates inserted 10 cm into the soil surface divided the study box along its length into two separate plots each 0.6 m wide and 5 m long. This arrangement allowed us to prepare and make rain events on a pair of contrasting smooth and rough surfaces simultaneously. The metal divide extended 5 cm above the soil.

The surface roughness was measured with an instantaneous-profile laser scanner (Darboux and Huang, 2003) on the lower 3.9-m portion of the study box with a horizontal resolution of 1.5 mm and a vertical resolution of 0.5 mm. Surface storage capacity was computed from the laser scanner data using the algorithm developed by Planchon and Darboux (2001).

Experimental Procedure

Box Preparation

The boxes were initially filled with air-dried surface soil. Before the series of experiment was started, seepage and drainage conditions were alternated to stabilize the soil structure.

Before each experiment, box preparation started with air drying of the soil surface using a fan. After the soil surface appeared dry, approximately 5 cm of the surface soil was turned using a hand trowel to help additional drying. Aggregates bigger than 5 cm were manually broken down using the hand tool. During box preparation, new soil was added to compensate for soil loss from the previous experiment to keep a similar amount of soil in both feeder and study boxes.

The prepared surface resembled a fine seedbed with no aggregates larger than 1 cm. The whole soil surface was smoothed down to obtain an even surface. The metal plates were then inserted to divide the study box in two equal areas. On one side of the study box, the surface was kept smooth. On the other side, depressions were molded by hand (Fig. 2). Depressions had a circular shape with 10 to 12 cm in diameter, a depth around 2 cm, and a density of approximately 40 depressions per squared meter.

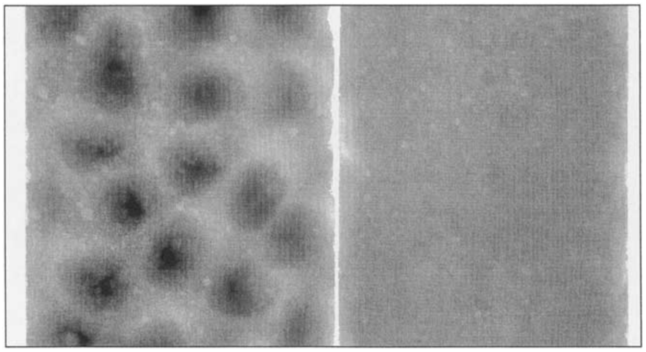

Fig. 2. Digital elevation model showing typical initial microtopographies of surfaces with depressions (left) or smooth (right) for a 67 by 126 cm area. Height increases from dark to light color. The left, right and center white strips are box edges and metal dividing plate.

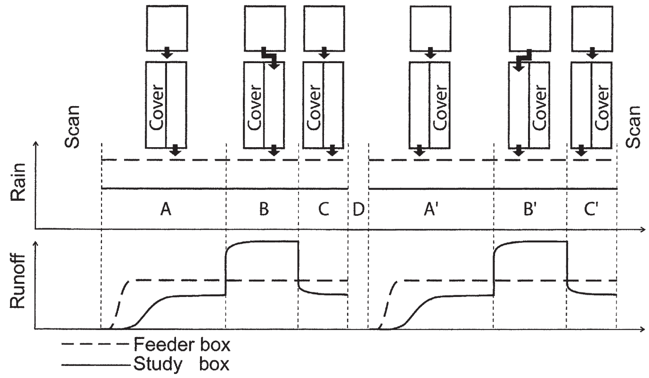

Fig. 3. An illustration of the sequence of operations conducted during a rain event on each side of the study box, showing changes in the plot exposed to rain and changes in feeder connection. Runoff and rain fluxes are schematic representations of measured data.

The day before the experiment, the soil boxes were set to horizontal position and a gentle rain (12 mm h^{-1}) was applied for 1 h to seal the soil surface without causing overland-flow and erosion. To equalize the moisture content, both feeder and study boxes were saturated from the bottom using the watering troughs. After saturation, the watering troughs were disconnected from the feeder box and the feeder box was free-drained overnight. The same operation was done on the study box if the experiment was to be conducted with free-drainage condition. For experiments under seepage condition, the watering troughs were left connected to the study box overnight.

Experiment

A total of eight experiments were conducted (Table 1). The slope of the study box was kept constant at 5% and the feeder box was set to 10%. Experiments were conducted with either seepage with water level at the watering trough maintained 5 cm above the soil surface or under free drainage condition. Experiments with seepage and drainage conditions were alternated to avoid a long-term evolution of soil properties during the experiment series. The sides with smooth surface and surface with depressions were also alternated to avoid a systematic bias due to potential differences in lateral conditions.

Except for Exp. B and G, each experiment consisted of a sequence of three rain events (Table 1). Rain intensities were kept constant at 24 mm h^{-1} on the study box and 48 mm h^{-1} on the feeder box through all experiments. During the first rain event, the feeder box surface was left uncovered so that water and particles were fed to the study box. During the second rain event, the feeder box surface was covered with a landscape fabric and almost clear water was fed to the study box. During the third rain event, the feeder box was uncovered.

A rain event consisted of a sequence of operations performed while rainfall was being applied to each of the two sides of the study box. Soil roughness was measured by a laser scanner before each rain event. Rain was first applied on the right side of the study box, with the left side protected from the rain with corrugated metal sheets (Fig. 3). Initially, the feeder box was disconnected from the study box (no runon—Stage A in Fig. 3). Runoff samples from the study box were collected in 1-L bottles at 1-min time step. Depending on the flow rate, samples were collected for the full 1 min or up to three-fourth full if the bottle would overflow (in this case, collection duration was recorded). After the runoff flux from the study box reached an apparent steady state, defined as three successive bottles with weight differences of <50 g, eight samples were taken simultaneously at the outlets of both boxes. Then, the outlet of the feeder box was connected to the upslope end of the study box (with runon—Stage B in Fig. 3). After the apparent steady state was reached at the outlet of the study box, another eight samples were collected. Then the boxes were disconnected (no runon—Stage C in Fig. 3) and, after few minutes, four samples were collected again at each outlet to check the similarity of flow rates before and after the connection.

After a rain event on the right-hand side, the metal cover was switched to the right side (Stage D in Fig. 3) and rain was applied to the left side. Switching the cover and restarting the rain took a couple of minutes. The rain procedure described above was applied to the left side (Stages A', B', and C' in Fig. 3). The duration of a rain event on a given combination surface–subsurface conditions depended on the time to reach apparent steady state and ranged from 30 to 80 min. The longest rain events were the first ones on surfaces with depressions under drainage condition and the shortest were the last events on smooth surfaces under seepage. After a rain event was applied to both sides, the metal cover was removed, and the surface on each side was visually inspected and soil microtopography was digitized by a laser scanner. This effort took approximately 1 h.

Table 1. Experimental conditions in the study box and number of rain events.

	Conditions in the study box			
Experiment	Near-surface gradient	Left side	Right side	Rain events
A	drainage	smooth	depressions	3
B	drainage	depressions	smooth	2
C	seepage	smooth	depressions	3
D	seepage	depressions	smooth	3
E	drainage	smooth	depressions	3
F	seepage	smooth	depressions	3
G	drainage	depressions	smooth	2
H	seepage	depressions	smooth	3

Runoff samples were weighted at collection time. After the end of an experiment, 3 to 5 mL of saturated alum [$AlK(SO_4)_2$] was added to each 1-L sample bottle to flocculate the solid fraction. The next day, clear supernatant was poured off and bottles were oven dried at 105°C. The dry bottles were weighted and water and sediment masses were calculated by subtracting the bottle tare weight. Runoff and particle fluxes were calculated from these data and adjusted for the duration of sample collection.

Statistical Analysis

We used the R Statistical Software (R Development Core Team, 2004) to analyze the results. To estimate the statistical significance of differences in time to runoff initiation between smooth surfaces and surfaces with depressions, paired *t* tests were computed for each of the subsurface conditions (drainage and seepage). The null hypothesis H_0 was the equality of the differences to zero. The alternative hypothesis was that the time to runoff was larger for the surfaces with depressions than for the smooth surfaces. Similar statistical procedures were also used for differences between apparent steady state fluxes at Stages A and C. We considered a Type-I statistical risk of 5%.

To identify the conditions where roughness had a significant effect on runoff at the outlet of the study box, an analysis of variance was conducted. The three variables were water flux, particle flux, and particle concentration. The full linear model was:

$$\begin{aligned}\text{Variable} = {} & \text{Subsurface condition} + \\ & \text{Experiment (Subsurface condition)} + \\ & \text{Runon condition} + \text{Rain event} + \\ & \text{Roughness type.}\end{aligned}$$

In the full model, the factor Experiment was nested in the factor "subsurface condition" because a given experiment had only one subsurface condition (either drainage or seepage).

To better identify the conditions where the roughness had a significant effect, submodels were run on subdatasets. First, the dataset was split according to the subsurface condition and then each of these subsets was split according to the upstream flow condition (with runon or without runon). We computed Type-III sums of squares (also known as Yates' weighted squares-of-means) and considered a Type-I statistical risk of 5%. Postulates of linear modeling (residuals with no bias, equality of residual variances, independence of residuals and Gaussian distribution of residuals) were checked graphically.

RESULTS AND DISCUSSION

Runoff Initiation

Runoff initiation may be affected by the storage of water in depressions and by infiltration. This section focuses on the relative effect of each of these two processes and their possible interaction.

Storage Capacity

Initial storage capacity was clearly a function of surface condition, and for all surfaces it decreased with added rainwater (Fig. 4). Differences between initially smooth surfaces and initial surfaces with depressions continued up to the second rain, at least. The depressions appeared to be more persistent for drainage than for seepage condition. The faster decline in storage capacity under seepage condition could be caused by both greater soil erodibility and runoff rates (Huang and Laflen, 1996; Huang, 1998).

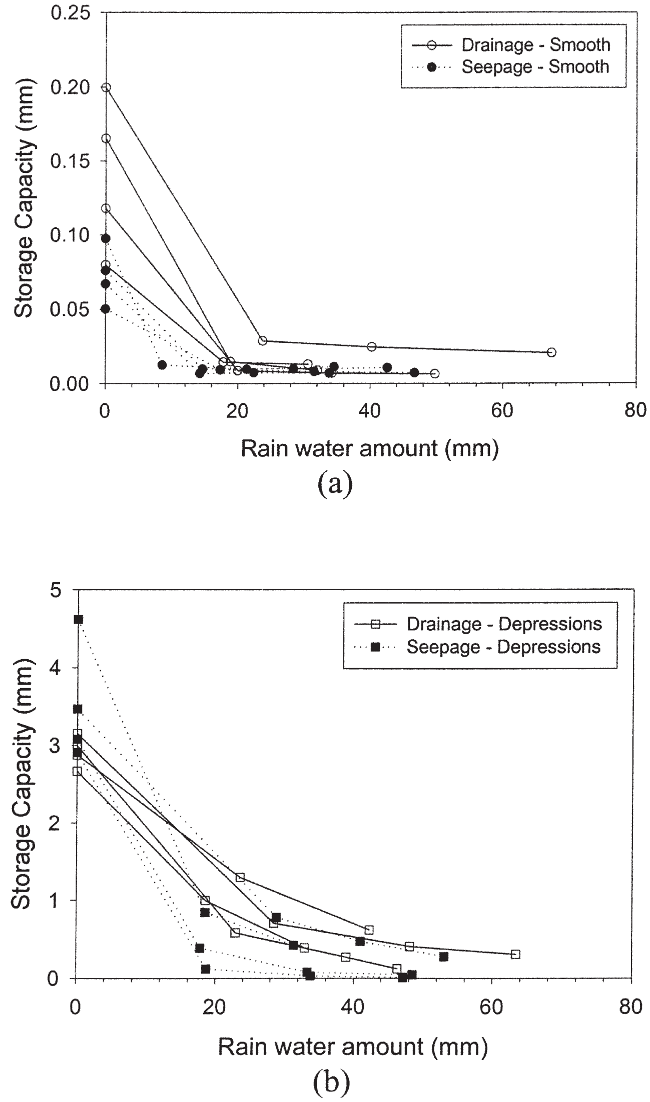

Fig. 4. Storage capacity calculated from laser scanned surfaces as function of cumulative rainfall for (a) smooth surfaces, and (b) surfaces with initial depressions. Note differences in vertical scales.

Time to Runoff Initiation

Under seepage condition, surface roughness did not affect the runoff initiation because surface depressions were initially filled and water was already running off the box outlet before a rain started (i.e., rainwater contributed directly to the runoff). The only exception was the first rain event of Exp. C (Table 2). The rain was accidentally started before seepage flow had time to fill completely the depressions.

Under drainage, and independently of the surface

Table 2. Time to runoff initiation as function of rain event, and subsurface and surface conditions.

	Drainage			Seepage	
Exp.	Smooth	Depressions	Exp.	Smooth	Depressions
	s			s	
		First rain event			
A	365	1180	C	0	570
B	315	840	D	0	0
E	160	765	F	0	0
G	210	690	H	0	0
Difference mean	606**			142 NS†	
		Second rain event			
A	120	180	C	0	0
B	100	140	D	0	0
E	70	240	F	0	0
G	90	180	H	0	0
Difference mean	90*			0 NS	
		Third rain event			
A	105	90	C	0	0
B	ND‡	ND	D	0	0
E	60	130	F	0	0
G	ND	ND	H	0	0
Difference mean	28 NS			0 NS	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
† NS, nonsignificant at the 0.1 probability level.
‡ ND, no data.

condition, there was always a delay between the start of a rain and runoff initiation, but such delay decreased with successive rain events (Table 2). For the first rain event, the difference in time to runoff initiation between smooth surfaces and surfaces with depressions was statistically significant. The time to runoff initiation was always longer for the surfaces with depressions than for the initially smooth surfaces. The difference in time to runoff initiation was of about 10 min, which represented a rainfall amount of about 4 mm. For the second rain event, the difference in time to runoff initiation was statistically significant but only of about 1 min. For the third rain, the difference in time to runoff initiation was not statistically significant. Under the drainage condition, a decrease in the time to runoff initiation with successive applied rainfalls was observed simultaneously with a decrease in depressional storage capacity. This is consistent with the fact that rainwater had to fill the depressions (at least some of them) before runoff could occur.

To separate the relative effects of storage and infiltration under drainage conditions, a time to depression filling was computed from roughness data and compared with the actual time to runoff initiation. This hypothetical time to depression filling was estimated by dividing the storage capacity by the area of the surface and the rainfall intensity. This assumes that there is no infiltration and that runoff starts only after all depressions are filled. The percentages of time to runoff initiation explained by the time to depression filling are displayed in Table 3. They were statistically significant for the first two rain events (Table 3). For the initially smooth surfaces, water storage by surface depressions explains in average only 8% of the runoff delay for the first rain and 2% for the second rainfall. In the cases with initial depressions, surface storage explains, in average, 50% of the time to runoff initiation for the first rainfall and 70% for the second rainfall.

These results suggest that although infiltration was the main process in explaining the time to runoff initiation for smooth surfaces, depressions largely contributed to the delay of runoff initiation. These results are consistent with previous experimental studies (Burwell et al., 1968; Burwell and Larson, 1969; Johnson et al., 1979; Cogo et al., 1984; Steichen, 1984). By trapping rainfall water in puddles and so preventing this water to run off, depressions have a direct effect on runoff initiation. Depressions could also have an indirect effect

Table 3. Ratios (shown as percentage) of estimated time to depression filling to observed time to runoff initiation as function of rain event, and surface conditions. Estimated time to depression filling represents runoff delay caused by filling of surface depressions under a hypothetical no infiltration condition.

	First rain event		Second rain event		Third rain event	
Exp.	Smooth	Depressions	Smooth	Depressions	Smooth	Depressions
	%					
A	8.2	40.1	3.6	58.8	3.5	67.7
B	7.9	53.5	2.2	62.6	ND‡	ND
E	11.1	52.4	1.9	62.4	1.7	44.8
G	5.7	62.6	2.4	107.0	ND	ND
Mean	8.2	52.2	2.5	72.7	2.6	56.3
Difference mean	43.9**		70.2**		53.6†	

** Significant at the 0.01 probability level.
† Significant at the 0.1 probability level.
‡ ND, no data.

Table 4. Water flux measured at the outlet of the study box as function of rain event, and subsurface and surface conditions.

	First rain event				Second rain event				Third rain event			
	No Runon		With Runon		No Runon		With Runon		No Runon		With Runon	
Exp.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.
	g s^{-1}											
	Drainage condition											
A	15.35	16.10	41.05	37.77	16.35	17.20	42.38	39.67	17.00	17.33	43.60	43.22
B	17.37	17.55	44.08	46.55	15.73	17.05	42.78	44.68	ND†	ND	ND	ND
E	18.12	19.92	45.42	44.87	17.98	18.82	44.17	44.32	18.46	19.12	43.37	44.88
G	17.45	19.23	42.18	45.67	17.55	18.42	43.15	45.73	ND	ND	ND	ND
Mean	17.07	18.20	43.18	44.22	16.90	17.87	43.12	43.60	17.73	18.22	43.98	44.05
	Seepage condition											
C	21.05	24.97	42.98	47.42	21.15	24.45	43.95	48.25	21.72	27.80	45.27	50.45
D	23.53	26.38	48.87	51.77	21.92	23.23	47.85	49.12	22.08	22.87	47.43	49.42
F	22.25	27.18	43.67	51.68	20.78	22.55	45.52	47.22	21.17	22.10	44.70	45.38
H	21.77	23.80	47.78	56.46	21.02	21.75	46.82	45.63	20.58	21.65	46.00	47.35
Mean	22.15	25.58	45.82	51.83	21.22	22.98	46.03	47.55	21.38	23.60	45.85	48.15

† ND, no data.

by keeping the near-surface soil under the puddle saturated and increasing the hydraulic gradient due to the ponding depth. As shown by Fig. 4, the subsurface condition also affected the persistence of depressions. Surface and subsurface conditions interacted to control the time to runoff initiation.

Although a single rainfall intensity was used in this research, it must be noted that the proportion of delay directly explained by depressional storage capacity is also a function of rainfall intensity. For lower rainfall intensities (but identical infiltrability and storage capacity), it is expected that more water would infiltrate before depressions get filled. In this case, calculations would show smaller direct effect of depressions on time to runoff initiation. On the other hand, indirect effects of depressions would be larger because depressions trap water and prevent runoff, hence allowing more water to infiltrate. The relative balance between the direct and indirect effects of depressions on runoff initiation remains to be specified.

Fluxes and Concentration at Apparent Steady State

For each rain event and surface condition, two types of apparent steady state were reached at the outlet of the study box. The first type of apparent steady state was reached when the boxes were not connected together (Fig. 3). There was no run-on inflow to the study box. Runoff water was due to the applied rain and to seepage flow when it was applied. For a given surface and a given rain event, this no-runon apparent steady state was reached once before the two boxes are connected together (Stage A) and once after they have been disconnected (Stage C). By comparing the fluxes for these two disconnected stages, we could assess the quality of the no-runon apparent steady state. Statistical analysis showed both water and particle fluxes were not statistically different before and after connection. Consequently, flux data from Stages A to C were averaged and analyzed as a single no-runon steady state data set (Tables 4, 5, and 6).

The second type of apparent steady state was reached once, when the boxes were connected together (Stage B). In this case, runoff was due to the applied rain, the run-on inflow and the seepage when it was applied.

The experiment was designed to analyze the effect of soil surface roughness on various flow conditions after an apparent steady state had been reached. Performances of the linear models for nested datasets are outlined in Table 7. All of these models are significant at the 5% probability level, but not all the factors are significant at that probability level.

Table 5. Particle flux measured at the outlet of the study box as function of rain event, and subsurface and surface conditions.

	First rain event				Second rain event				Third rain event			
	No runon		With runon		No runon		With runon		No runon		With runon	
Exp.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.
	g s^{-1}											
	Drainage condition											
A	0.14	0.15	0.85	0.62	0.13	0.16	0.47	0.47	0.18	0.20	0.77	0.60
B	0.11	0.17	0.68	0.72	0.11	0.22	0.42	0.58	ND†	ND	ND	ND
E	0.37	0.35	1.67	1.03	0.30	0.28	1.10	0.63	0.30	0.32	1.75	1.25
G	0.28	0.35	0.98	0.87	0.18	0.27	0.62	0.55	ND	ND	ND	ND
Mean	0.22	0.25	1.05	0.81	0.18	0.23	0.65	0.56	0.24	0.26	1.26	0.93
	Seepage condition											
C	0.60	0.58	1.92	1.67	0.63	0.70	1.87	1.73	0.53	0.67	1.85	1.82
D	0.85	0.70	2.97	2.17	0.67	0.65	2.30	1.78	0.72	0.80	3.25	3.12
F	0.50	0.42	1.45	1.25	0.58	0.42	1.47	1.10	0.47	0.62	1.60	2.33
H	0.72	0.85	3.12	3.25	0.95	0.93	3.20	3.75	0.85	1.03	3.73	4.87
Mean	0.67	0.64	2.36	2.08	0.71	0.68	2.21	2.09	0.64	0.78	2.61	3.03

† ND, no data.

Table 6. Concentration of particles measured at the outlets of the study box as function of rain event, and subsurface and surface conditions.

	First rain event				Second rain event				Third rain event			
	No Runon		With Runon		No Runon		With Runon		No Runon		With Runon	
Exp.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.	Smooth	Depres.
	g kg^{-1}											
	Drainage condition											
A	8.9	9.0	20.7	15.5	8.1	9.3	11.0	11.8	10.8	11.5	17.6	13.9
B	6.0	9.5	15.5	15.4	7.0	12.7	9.7	13.0	ND†	ND	ND	ND
E	20.2	17.6	36.7	23.0	16.7	15.1	24.9	14.3	16.2	16.6	39.4	27.8
G	16.2	18.2	23.3	19.0	10.4	14.5	14.3	12.0	ND	ND	ND	ND
Mean	12.9	13.6	24.0	18.2	10.6	12.9	15.0	12.8	13.5	14.0	28.5	20.9
	Seepage condition											
C	28.5	23.4	44.6	35.1	29.9	28.6	42.5	35.9	24.6	24.0	40.9	36.0
D	36.1	26.5	60.7	41.8	30.4	28.0	48.1	36.3	32.4	35.0	68.5	63.1
F	22.5	15.3	33.2	24.2	28.1	18.5	32.2	23.3	22.0	27.9	35.8	51.4
H	32.9	35.7	65.2	57.6	45.2	42.9	68.3	82.2	41.3	47.7	81.2	102.8
Mean	30.0	25.2	50.9	39.7	33.4	29.5	47.8	44.4	30.1	33.6	56.6	63.3

† ND, no data.

As expected from the experimental design, the effects of subsurface and runon conditions on water flux, particle flux, and particle concentration were statistically significant (Table 8).

There was significant variability among experiments, as demonstrated by the significance of the factor "experiment" when all data are considered and also under drainage condition (Table 8). A large variability of the results is often encountered in soil erosion studies (Wendt et al., 1986; Nearing et al., 1999; Tiwari et al., 2000). This variability is partly due to the difficulty of obtaining identical initial conditions. This concern was addressed through the use of paired plots that helped to palliate differences among experiments. The factor "experiment" was not significant in explaining the water flux under seepage conditions while it was significant for the particle flux. The underlying reason remains unclear.

At apparent steady state, roughness had a significant effect on water flux except for the condition "drainage with runon" (Table 8). The surface with initial depressions yielded larger water flux than the smooth side (Table 4). Nevertheless, it should be pointed out that the difference in fluxes between the two roughness conditions was mostly in the range of 10% (Table 4). The effect of roughness on particle flux and concentration was mostly nonsignificant. If such effect exists, its amplitude is probably very low and could not be characterized with the current dataset.

Two or three successive rainfalls were applied on each surface. For a given surface, the main difference between the initial conditions of each rain event was soil surface properties. So, the factor "rain event" could be used to assess the evolution of the roughness effect with successive rainfalls. Among successive rainfalls, the upstream input of sediment was varied, possibly modifying the sediment output. The factor "rain event" is significant on water flux, particle flux, and particle concentration only when the whole dataset is considered, but no conclusion can be drawn about the effect of the successive rain events because values of "rain event" coefficients lack statistical significance. Overall, it appears that successive rains did not change much the runoff characteristics and that effect of initial roughness was larger that the effect of successive rains.

Overall, the analysis points out initial depressions had a continuing effect by increasing the water flux at apparent steady state. In the meantime, the storage capacities of the surfaces with initial depressions decreased sharply with the successive rain events. This leads to the rejection of any hypothesis connecting the higher runoff fluxes with the storage capacity of the surfaces. Therefore, the decrease in infiltration should be related to the initial presence of depressions and not to their persistence.

Results of the present study are not in total agreement with previous experiments reported in the literature. Prior studies showed that an increased roughness either decreased water runoff (Johnson et al., 1979; Cogo et al., 1984) or had no significant effect on it (Burwell et al., 1968; Burwell and Larson, 1969; Helming et al.,

Table 7. Outline of linear models' results considering the whole dataset and its subsets.

Data sets			Variables df	Water flux RSE†	Adj.-R^2‡	Level	Particle flux RSE	Adj.-R^2	Level	Particle concentration RSE	Adj.-R^2	Level
All data			76	107.2	0.98	***	28.9	0.76	***	8.3	0.80	***
	Drainage		32	66.3	0.99	***	11.8	0.77	***	4.1	0.67	***
		No runon	13	34.5	0.77	***	2.4	0.79	***	2.2	0.72	***
		With runon	13	84.6	0.45	*	10.7	0.77	***	4.0	0.77	***
	Seepage		40	116.7	0.98	***	29.1	0.81	***	9.2	0.74	***
		No runon	17	82.0	0.54	***	5.2	0.73	***	4.2	0.74	***
		With runon	17	138.2	0.42	*	24.0	0.83	***	9.7	0.77	***

* Significant at the 0.05 probability level.
*** Significant at the 0.001 probability level.
† RSE, residual standard error.
‡ Adj.-R^2, adjusted coefficient of determination.

Table 8. Significance of the factors used to explain water fluxes and particle fluxes and concentrations at apparent steady state.

		Factors	Subsurface			Runon			Experiment			Roughness			Rain event		
		Variables§	Fw	Fp	Co	Fw	Fp	Co	Fw	Fp	Co	Fw	Fp	Co	Fw	Fp	Co
All data			***	***	***	***	***	***	**	***	***	***	NS‡	NS	*	*	**
	Drainage					***	***	***	***	***	***	*	NS	NS	NS	*	**
		No runon							***	***	***	**	†	NS	NS	NS	NS
		With runon							**	***	***	NS	*	*	NS	**	**
	Seepage					***	***	***	NS	***	***	***	NS	NS	*	+	*
		No runon							NS	***	***	***	NS	NS	*	NS	NS
		With runon							NS	***	***	**	NS	NS	NS	**	*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Significant at the 0.1 probability level.
‡ NS, nonsignificant at the 0.1 probability level.
§ Fw, flux of water; Fp, flux of particles; Co, concentration of particles.

1998). With regard to particle transfer, it was found an increased roughness either decreased soil loss (Johnson et al., 1979; Cogo et al., 1984) or increased it (Helming et al., 1998).

The reason for these different results probably lies in differences in soil properties, roughness characteristics, and experiment setups. In the current experiment, aggregates had small diameters and their size was kept somewhat identical for all roughness conditions. The roughness of the surface was dominated by the 'macro'-scale depressions that our experiment specifically targeted. The other studies varied the aggregate size (either by tillage or by sieving), also varying the size of the pores open to the surface. The larger the aggregates were, the larger the pores, probably explaining the decrease in runoff rate with the increase in aggregate size. Such phenomenon was not likely to occur in our experiment.

CONCLUSIONS

A laboratory experiment was conducted to assess effects of soil surface depressions on runoff initiation, water runoff, and soil loss under different subsurface moisture regimes (seepage and drainage) and upstream flow conditions (with or without runon). Depressions delayed runoff initiation by storing water in puddles and enhancing infiltration. Once an apparent steady state was reached, surfaces with initial depressions slightly increased water flux compared with initially smooth surfaces. This effect occurred for both drainage and seepage conditions and persisted even after the surface storage capacity became low. Results showed that the roughness had no significant effect on particle flux and concentration.

Considering the steady-state water flux is uncommon in field conditions, and even at this stage, the effect of surface depressions is limited to a slight increase in water flux, we conclude that the only assured soil and water conservation benefit from soil surface roughness is the delay in runoff initiation before the entire field is fully saturated and contributing to runoff.

In this study, the relationship between roughness, infiltration and runoff initiation was assessed for a single rainfall intensity and proved to be significant. To achieve a better implementation of this relationship in water erosion models, the present results will need to be extended for a range of rainfall intensities.

In future experiments, it may be important to partition random roughness into subcomponents such as aggregate size and mound-and-depression pattern to better explain roughness effect on runoff and erosion. Comparison of the present results reveals the complexity of the interaction between roughness, overland flow and erosion. At this point, our knowledge is still insufficient to offer a mechanism for the roughness effects on overland flow and sediment detachment and transport.

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